Factorial Basis Representation of Rational Numbers

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From 'A Course of Pure Mathematics' by G. H. Hardy. Chapter 1, Miscellaneous Examples.

Miscellaneous example* #2 at the end of chapter 1 in Hardy's 'Pure Mathematics' presents us with a fascinating result. The theorem feels like what the 'basis-representation-theorem' is for integers, but for rational numbers . . . beautiful!

Factorial Representation Theorem†

Any positive rational number can be expressed in one and only one way in the form

$$a_1 + \frac{a_2}{1 \cdot 2} + \frac{a_3}{1 \cdot 2 \cdot 3} + \ldots + \frac{a_k}{1 \cdot 2 \cdot 3 \cdot \ldots \cdot k},$$

where $a_1, a_2, \ldots, a_k$ are integers, and

$$0 \leq a_1, \quad 0 \leq a_2 < 2, \quad 0 \leq a_3 < 3, \quad \ldots, \quad 0 < a_k < k$$

Observations that led to the proof.

The crux of the problem seemed to be showing that *every* rational number has such a representation - Proving uniqueness didn't seem as daunting. Here are some thoughts that pointed me in a certain direction that led me to the proof below.

We know that any rational number‡, say $\frac{m}{q}$, can be written as an integer part, i, plus a fractional part, $\frac{p}{q}$, such that $\frac{m}{q} = i + \frac{p}{q}$, where $0 \leq \frac{p}{q} < 1$ (note that i can be zero).

So if we're trying to represent any positive rational number $\frac{m}{q}$ in the form of the theorem then the integer a_1 wants to play the role of the integer part, i, and the remainder of the expression $\frac{a_2}{2!} + \frac{a_3}{3!} + \ldots + \frac{a_k}{k!}$ looks to be playing the role of the rational part, $\frac{p}{q}$, where,

$$0 \leq \frac{a_2}{2!} + \frac{a_3}{3!} + \ldots + \frac{a_k}{k!} < 1$$

It seemed to me a good idea to forget about the integer a_1 and just focus on the integers $a_2, a_3, \ldots, a_k$. In other words, prove the theorem for rational numbers $\frac{p}{q}$, where $0 \leq \frac{p}{q} < 1$, then it should be trivial to extend it to ALL rational numbers by tacking the a_1 back on at the end

*Hardy doesn't call them 'Exercises' or 'Questions', but that's what they are, math exercises for the student.

†The theorem is not named in the text, so I named it.

‡Every variable, or constant (eg. a_1, a_k, m, n, i, p, q) in this paper is going to represent a non-negative integer. We aren't dealing with 'real numbers' here, just non-negative rational numbers which we will always discuss in terms of one integer divided by another integer, like $\frac{p}{q}$.

of the proof. Also, it started to become clear that including zero (that is, not JUST positive rational numbers) was going to simplify the task*.

At first, it wasn't remotely obvious to me how I'd go about calculating the values of the integers $a_2, a_3, \ldots, a_k$ for a given rational number $\frac{p}{q}$ (where $0 \leq \frac{p}{q} < 1$) let alone that it would be unique.

After playing around for a while, and finally figuring out a way to calculate the variables $a_2, a_3, \ldots, a_k$ for a given rational number, (it's kinda like doing long-division) a few thing started to jump out at me. For example, look at these numbers,

$$\frac{1}{2} = \frac{1}{1 \cdot 2} = \frac{2! - 1}{2!}$$
$$\frac{5}{6} = \frac{1}{1 \cdot 2} + \frac{2}{1 \cdot 2 \cdot 3} = \frac{1 \cdot 3}{1 \cdot 2 \cdot 3} + \frac{2}{1 \cdot 2 \cdot 3} = \frac{3 + 2}{6} = \frac{3! - 1}{3!}$$
$$\frac{23}{24} = \frac{1}{1 \cdot 2} + \frac{2}{1 \cdot 2 \cdot 3} + \frac{3}{1 \cdot 2 \cdot 3 \cdot 4} = \frac{1 \cdot 3 \cdot 4}{1 \cdot 2 \cdot 3 \cdot 4} + \frac{2 \cdot 4}{1 \cdot 2 \cdot 3 \cdot 4} + \frac{3}{1 \cdot 2 \cdot 3 \cdot 4} = \frac{12 + 8 + 3}{24} = \frac{4! - 1}{4!}$$

An obvious pattern has emerged! It seems to be the case that if we assign the largest possible values to the variables, from a_2 up to a_k (with all subsequent variables being zero) we get the rational number $\frac{k!-1}{k!}$, which is as close to 1 as you can get with a denominator of $k!$ without actually hitting 1. (What happens if you add $\frac{1}{k!}$ to $\frac{k!-1}{k!}$?) This turned out to be a pretty useful observation, and it became my 'Lemma 1' in the proof below.

Also, if we assign zeros to all the variables then naturally we get $\frac{0}{k!}$, plus it's pretty obvious to figure out how to make the smallest such non-zero rational number $\frac{1}{k!}$. Then thinking about continually adding $\frac{1}{k!}$ to the result, we get an idea about how the a_i variables change as you keep incrementing by $\frac{1}{k!}$.

So if we restrict ourselves to using only $a_2, a_3, \ldots, a_k$, then we can generate the smallest rational number $(\frac{0}{k!})$ and the largest $(\frac{k!-1}{k!})$ where $0 \leq \frac{a_2}{2!} + \frac{a_3}{3!} + \ldots + \frac{a_k}{k!} < 1$.

One further observation to help understand the motivation behind this proof is that by using combinatorics we can count how many possible combinations of a_i's there are. So, we have two choices for the a_2 variable (0, 1), combined with three choices for the a_3 variable (0, 1, 2), combined with four choices for the a_4 variable (0, 1, 2, 3), ... combined with k choices for the a_k variable (0, 1, 2, ..., $k-1$), which gives us $2 \cdot 3 \cdot 4 \cdot \cdot \cdot k = k!$ possible different sums.

Hmmmmm, the following set has $k!$ members, $\{\frac{0}{k!}, \frac{1}{k!}, \frac{2}{k!}, \ldots, \frac{k!-1}{k!}\}$. With a little algebraic tinkering we can see that this set contains each of the rational numbers between zero and one with denominators from 2 up to k, so if we let k grow without bound then we should get a set that contains all the rational numbers between zero and one.

So that, plus one or two other thoughts is what led me to the proof below. I won't spoil the rest of it; to find out, go ahead and read the rest of the paper!

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*Did you notice how the theorem restricts the last integer, a_k, to be strictly greater than zero, unlike all the other variables? We loosen up that restriction by allowing a_k to be equal to zero so that all the variables are treated the same. At the very end of the proof it's trivial to reintroduce that restriction on the integer a_k.

Lemma 1

$$\frac{1}{2!} + \frac{2}{3!} + \ldots + \frac{k-1}{k!} = \frac{k!-1}{k!}, \quad \text{for all integers } k \geq 2$$

Proof

This equality is straightforward to demonstrate by induction, since $\frac{1}{2!} = \frac{2!-1}{2!}$ and,

$$\begin{aligned}
& \frac{1}{2!} + \frac{2}{3!} + \ldots + \frac{k-2}{(k-1)!} + \frac{k-1}{k!} \\
&= \frac{(k-1)!-1}{(k-1)!} + \frac{k-1}{k!} \\
&= \frac{k((k-1)!-1)}{k(k-1)!} + \frac{k-1}{k!} \\
&= \frac{k! - k + k - 1}{k!} \\
&= \frac{k!-1}{k!}
\end{aligned}$$

...thus establishing Lemma 1 for all values of $k \geq 2$. QED.

The following lemma captures an idea that is perhaps most easily grasped by analogy to the basis representation theorem for integers. For base-ten numbers we can say,

$$1 \cdot 10^k > 9 \cdot 10^{k-1} + 9 \cdot 10^{k-2} + \ldots + 9 \cdot 10^2 + 9 \cdot 10^1 + 9 \cdot 10^0$$

The above inequality is merely stating that any single power of ten is bigger than the sum of every smaller power of ten, each times 9. For example, 1000 is bigger than 999. Read the statement of the inequality in Lemma 2 with this idea in mind.

Lemma 2

For integers i, k where $2 \leq i < k$,

$$\frac{1}{i!} > \frac{i}{(i+1)!} + \frac{i+1}{(i+2)!} + \ldots + \frac{k-2}{(k-1)!} + \frac{k-1}{k!}$$

Proof

$$\begin{aligned}
& \frac{i}{(i+1)!} + \frac{i+1}{(i+2)!} + \ldots + \frac{k-2}{(k-1)!} + \frac{k-1}{k!} \\
&= \left(\frac{1}{2!} + \frac{2}{3!} + \ldots + \frac{k-1}{k!}\right) - \left(\frac{1}{2!} + \frac{2}{3!} + \ldots + \frac{i-1}{i!}\right) \\
&= \frac{k!-1}{k!} - \frac{i!-1}{i!} \qquad \text{(by Lemma 1)} \\
&= \frac{k!}{k!} - \frac{1}{k!} - \frac{i!}{i!} + \frac{1}{i!} \\
&= \frac{1}{i!} - \frac{1}{k!} \\
&< \frac{1}{i!} \qquad \text{QED.}
\end{aligned}$$

Definitions

For integer $k \geq 2$, and integers $a_2, a_3, \ldots, a_k$, we define the following sets,

$$\mathcal{S}_k = \{\frac{a_2}{2!} + \frac{a_3}{3!} + \ldots + \frac{a_k}{k!} \quad | \quad 0 \leq a_2 < 2, \;\; 0 \leq a_3 < 3, \;\; \ldots, \;\; 0 \leq a_k < k\},$$
$$\mathcal{F}_k = \{\frac{0}{k!}, \;\; \frac{1}{k!}, \;\; \frac{2}{k!}, \;\; \ldots, \;\; \frac{k!-1}{k!}\}$$

If $a \in \mathcal{S}_k$, then the sum $\frac{a_2}{2!} + \frac{a_3}{3!} + \ldots + \frac{a_k}{k!}$, where $k \geq 2$, and $0 \leq a_2 < 2, \;\; 0 \leq a_3 < 3, \;\; \ldots, \;\; 0 \leq a_k < k$, is called the "factorial-representation" of a.

Lemma 3

$$\mathcal{S}_k = \mathcal{F}_k$$

Proof

To show that the set $\mathcal{S}_k$ is the same as $\mathcal{F}_k$, it suffices to show that if $\frac{a}{b} \in \mathcal{S}_k$ then $0 \leq \frac{a}{b} < 1$ and $\frac{a}{b} = \frac{p}{k!}$ for some p, and that the size of $\mathcal{S}_k$ is the same as $\mathcal{F}_k$.

It's clear that the set $\mathcal{F}_k$ contains every rational number with denominator $k!$ where p is an integer and $0 \leq \frac{p}{k!} < 1$ and that the size of $\mathcal{F}_k$ is $k!$.

The smallest member of the set $\mathcal{S}_k$ is $\frac{0}{k!}$ and occurs when all the variables of the sum are set to zero. Furthermore, the largest member of the set occurs when all the variables of the sum are set to their maximum value, which gives us $\frac{k!-1}{k!}$ as shown in Lemma 1.

We also note that every member of $\mathcal{S}_k$ can be written as a rational number with $k!$ as the denominator, like so,

$$\frac{a_2}{2!} + \frac{a_3}{3!} + \ldots + \frac{a_{k-1}}{(k-1)!} + \frac{a_k}{k!} = \frac{k \cdot (k-1) \cdot \cdot \cdot 3 \cdot a_2}{k!} + \frac{k \cdot (k-1) \cdot \cdot \cdot 4 \cdot a_2}{k!} + \ldots + \frac{k \cdot a_{k-1}}{k!} + \frac{a_k}{k!}$$

Therefore any member of the set $\mathcal{S}_k$ can be written as $\frac{p}{k!}$ for some integer p, where

$$0 = \frac{0}{k!} \leq \frac{p}{k!} \leq \frac{k!-1}{k!} < \frac{k!}{k!} = 1, \quad \text{hence,} \quad 0 \leq \frac{p}{k!} < 1$$

Furthermore, each possible assignment of values to the variables of the factorial-representation of $\frac{p}{k!}$ produces a *unique* member of the set $\mathcal{S}_k$*.

For if this weren't true and both $\frac{p}{k!} = \frac{a_2}{2!} + \frac{a_3}{3!} + \ldots + \frac{a_k}{k!}$ and $\frac{p}{k!} = \frac{b_2}{2!} + \frac{b_3}{3!} + \ldots + \frac{b_k}{k!}$ for different variables $a_2, a_3, \ldots, a_k$ and $b_2, b_3, \ldots, b_k$, then we can arrive at a contradiction as follows.

*... and a good thing too otherwise the set wouldn't be well defined!

First suppose that $a_i \neq b_i$, where $i \leq k$, is the first such pair of variables that differ. In other words, $a_2 = b_2,\ a_3 = b_3, \ldots,\ a_{i-1} = b_{i-1},\ a_i \neq b_i$. Without loss of generality, further suppose that $a_i > b_i$. Because of the equality of the two different representations for $\frac{p}{k!}$ we can now write,

$$\frac{a_i}{i!} + \frac{a_{i+1}}{(i+1)!} + \frac{a_{i+2}}{(i+2)!} + \ldots + \frac{a_k}{k!} = \frac{b_i}{i!} + \frac{b_{i+1}}{(i+1)!} + \frac{b_{i+2}}{(i+2)!} + \ldots + \frac{b_k}{k!}$$

$$\Leftrightarrow \qquad \frac{a_i - b_i}{i!} = \frac{b_{i+1} - a_{i+1}}{(i+1)!} + \frac{b_{i+2} - a_{i+2}}{(i+2)!} + \ldots + \frac{b_k - a_k}{k!} \tag{1}$$

But $a_i - b_i \geq 1$, so

$$\tfrac{a_i - b_i}{i!} \geq \tfrac{1}{i!}.$$

In the case that $i = k$ we get an immediate contradiction because equation (1) tells us that $\frac{a_i - b_i}{i!} = 0$ which is clearly false.

So let's carry on assuming that $i < k$ and examine one of the terms on the right-side of (1), say the first one $\frac{b_{i+1} - a_{i+1}}{(i+1)!}$. We can see that since $0 \leq b_{i+1} \leq i$ and $0 \leq a_{i+1} \leq i$ that,

$$\tfrac{i-0}{(i+1)!} \geq \tfrac{b_{i+1} - a_{i+1}}{(i+1)!},$$

and hence by extension to the other terms,

$$\tfrac{i}{(i+1)!} + \tfrac{i+1}{(i+2)!} + \ldots + \tfrac{k-1}{k!} \geq \tfrac{b_{i+1} - a_{i+1}}{(i+1)!} + \tfrac{b_{i+2} - a_{i+2}}{(i+2)!} + \ldots + \tfrac{b_k - a_k}{k!}.$$

Furthermore, Lemma 2 tells us that $\frac{1}{i!} > \frac{i}{(i+1)!} + \frac{i+1}{(i+2)!} + \ldots + \frac{k-1}{k!}$, so we can string all our inequalities together as follows,

$$\tfrac{a_i - b_i}{i!} \geq \tfrac{1}{i!} > \tfrac{i}{(i+1)!} + \ldots + \tfrac{k-1}{k!} \geq \tfrac{b_{i+1} - a_{i+1}}{(i+1)!} + \ldots + \tfrac{b_k - a_k}{k!},$$

and hence,

$$\tfrac{a_i - b_i}{i!} > \tfrac{b_{i+1} - a_{i+1}}{(i+1)!} + \ldots + \tfrac{b_k - a_k}{k!},$$

But in equation (1) we had deduced that $\frac{a_i - b_i}{i!} = \frac{b_{i+1} - a_{i+1}}{(i+1)!} + \ldots + \frac{b_k - a_k}{k!}$ which contradicts the strict inequality above.

Therefore our assumption that there can be a second set of variables representing the same rational number $\frac{p}{k!}$ must be false. Therefore any assignment of values to the variables of the sum $\frac{a_2}{2!} + \frac{a_3}{3!} + \ldots + \frac{a_k}{k!}$ produces a *unique* number in the set $\mathcal{S}_k$.

Now we can count the number of members of $\mathcal{S}_k$, by looking at all the possible combinations of values for the variables $a_2, a_3, \ldots, a_k$. There are 2 choices for the variable a_2, combined with 3 choices for a_3, combined with 4 choices for a_4, …, combined with k choices for a_k.

Therefore the total number of combinations of values that can be assigned to all the variables of $\frac{a_2}{2!} + \frac{a_3}{3!} + \frac{a_4}{4!} + \ldots + \frac{a_k}{k!}$ is $2 \cdot 3 \cdot 4 \cdots k = k!$. Since each set of assignments creates a *unique* member of the set, then the size of the set $\mathcal{S}_k$ is $k!$ which is also the size of the set $\mathcal{F}_k$. Recalling from above that any member of the set $\mathcal{S}_k$, say $\frac{a}{b}$, can be written as $\frac{a}{b} = \frac{p}{k!}$, for some p where $0 \leq \frac{p}{k!} < 1$ then $\mathcal{S}_k = \mathcal{F}_k$.

QED.

Corollary to Lemma 3

The factorial-representation for every non-negative rational number $\frac{p}{k!} \in \mathcal{F}_k$ is *unique*.

The corollary is a direct result of the fact that the sets $\mathcal{F}_k$ and $\mathcal{S}_k$ are equal, which you may recall means $a \in \mathcal{F}_k \Leftrightarrow a \in \mathcal{S}_k$.

Definitions

$$\mathcal{F} = \bigcup_{k=2}^{\infty} \mathcal{F}_k$$
$$\mathcal{S} = \bigcup_{k=2}^{\infty} \mathcal{S}_k$$
$$\mathbb{Q}_{01} = \{\frac{p}{q} \mid p, q \in \mathbb{Z},\ \text{where } q \geq 2,\ 0 \leq p < q,\ \text{and } \gcd(p, q) = 1\}$$

$\mathcal{F}$ is the set of ALL non-negative rational numbers, less than one, with all possible factorials as the denominator.

$\mathcal{S}$ is the set of ALL non-negative rational numbers, less than one, formed by every factorial-representation possible.

Finally, $\mathbb{Q}_{01}$ is the set of ALL non-negative rational numbers less than one, where p and q are co-prime. We specify the co-prime condition to get unique members of the set, otherwise the set isn't well defined.

Recall that two sets, X and Y are equal if and only if, for all a,

$$a \in X \Leftrightarrow a \in Y.$$

Lemma 4

$$\mathbb{Q}_{01} = \mathcal{S}$$

Proof

Lemma 3 tells us that the sets $\mathcal{F}_k$ and $\mathcal{S}_k$ are equal, so clearly,

$$\mathcal{F} = \bigcup_{k=2}^{\infty} \mathcal{F}_k = \bigcup_{k=2}^{\infty} \mathcal{S}_k = \mathcal{S},$$

hence,

$$\mathcal{F} = \mathcal{S}. \tag{2}$$

For all $\frac{p}{k} \in \mathbb{Q}_{01}$ we have $\frac{p}{k} \in \mathcal{F}_k$ because,

$$\frac{p}{k} = \frac{2 \cdot 3 \cdot \cdot \cdot (k-1)}{2 \cdot 3 \cdot \cdot \cdot (k-1)} \cdot \frac{p}{k} = \frac{2 \cdot 3 \cdot \cdot \cdot (k-1) \cdot p}{k!},$$

and because $\mathcal{F}_k \subset \mathcal{F}$, then $\frac{p}{k} \in \mathcal{F}$.

Conversely for all $\frac{p}{k!} \in \mathcal{F}$, then $\frac{p}{k!} \in \mathbb{Q}_{01}$ as follows,

Let $m = \frac{p}{\gcd(p,k!)}$ and $n = \frac{k!}{\gcd(p,k!)}$.

$$\frac{p}{k!} = \frac{p * \frac{1}{\gcd(p,k!)}}{k! * \frac{1}{\gcd(p,k!)}} = \frac{m}{n},$$

and since $\gcd(m,n) = 1$ then $\frac{m}{n} \in \mathbb{Q}_{01}$, that is; $\frac{p}{k!} \in \mathbb{Q}_{01}$.

Therefore, for all a; $a \in \mathcal{F} \Leftrightarrow a \in \mathbb{Q}_{01}$, which means, $\mathcal{F} = \mathbb{Q}_{01}$, hence by the transitivity of equality, and equation (2) above,

$$\mathcal{S} = \mathbb{Q}_{01}.$$

QED.

Corollary to Lemma 4

The factorial-representation for every rational number in $\mathbb{Q}_{01}$ is *unique*.

The corollary is a direct result of the fact that the sets $\mathcal{S}$ and $\mathbb{Q}_{01}$ are equal.

That statement is sufficient to prove the corollary, so you can skip to the actual proof of the "Factorial Representation Theorem" if you like, however to shed a little more light on why this corollary is true, it's worth looking at a few details.

We first note that $\mathcal{F}_2 \subset \mathcal{F}_3 \subset \mathcal{F}_4 \subset \ldots$ because, for all $\frac{p}{k!} \in \mathcal{F}_k$, since $\frac{p}{k!} = \frac{(k+1) \cdot p}{(k+1) \cdot k!} = \frac{(k+1) \cdot p}{(k+1)!}$, and $\frac{(k+1) \cdot p}{(k+1)!} \in \mathcal{F}_{k+1}$, therefore $\frac{p}{k!} \in \mathcal{F}_{k+1}$, hence $\mathcal{F}_k \subset \mathcal{F}_{k+1}$.

Since each successive set's size grows larger, then by induction it is straightforward to conclude that $\mathcal{F}_2 \subset \mathcal{F}_3 \subset \mathcal{F}_4 \subset \ldots$, for all $\mathcal{F}_i$, $i \geq 2$.

Similarly $\mathcal{S}_2 \subset \mathcal{S}_3 \subset \mathcal{S}_4 \subset \ldots$, because for all $\frac{a_2}{2!} + \frac{a_3}{3!} + \ldots + \frac{a_k}{k!} \in \mathcal{S}_k$, since $\frac{a_2}{2!} + \frac{a_3}{3!} + \ldots + \frac{a_k}{k!} = \frac{a_2}{2!} + \frac{a_3}{3!} + \ldots + \frac{a_k}{k!} + \frac{0}{(k+1)!}$ and $\frac{a_2}{2!} + \frac{a_3}{3!} + \ldots + \frac{a_k}{k!} + \frac{0}{(k+1)!} \in \mathcal{S}_{k+1}$ then, $\frac{a_2}{2!} + \frac{a_3}{3!} + \ldots + \frac{a_k}{k!} \in \mathcal{S}_{k+1}$. Hence $\mathcal{S}_k \subset \mathcal{S}_{k+1}$.

Since each successive set's size grow larger, then by induction it is straightforward to conclude that $\mathcal{S}_2 \subset \mathcal{S}_3 \subset \mathcal{S}_4 \subset \ldots$, for all $\mathcal{S}_i$, $i \geq 2$.

This infinite chain of supersets helps us to think about the meaning of our new sets $\mathcal{F}$ and $\mathcal{S}$, each of which are defined as a union of an infinite sequence of $\mathcal{F}_i$'s and $\mathcal{S}_i$'s.

We can imagine that as we build up either master-set by including each successive $\mathcal{F}_i$ or $\mathcal{S}_i$, that either we're only adding new elements to the ones that we've already gathered up, or we're simply tossing the whole previous collection out, then using the entire contents of the new largest set in its place. Either way of thinking about building up our infinite union of sets is valid.

So once a particular rational number $\frac{p}{q} \in \mathbb{Q}_{01}$ finds it's way into one of the sets $\mathcal{S}_i$ for some i, then it will forever be in all successive sets $\mathcal{S}_n$ for $n > i$, and it's factorial-representation is unique within each of those successively larger sets.

Factorial Representation Theorem

Any positive rational number can be expressed in one and only one way in the form

$$a_1 + \frac{a_2}{1 \cdot 2} + \frac{a_3}{1 \cdot 2 \cdot 3} + \ldots + \frac{a_k}{1 \cdot 2 \cdot 3 \cdot \ \ldots \ \cdot k},$$

where $a_1, a_2, \ldots, a_k$ are integers, and

$$0 \leq a_1, \quad 0 \leq a_2 < 2, \quad 0 \leq a_3 < 3, \quad \ldots, \quad 0 < a_k < k$$

Proof

Thanks to Euclid we know that for all integers $j \geq 0$ and $q > 0$, there exist *unique* integers i and p such that,

$$\begin{aligned} & j = i \cdot q + p \ ; \quad 0 \leq p < q \\ \Leftrightarrow \quad & \frac{j}{q} = i + \frac{p}{q} \ ; \quad 0 \leq \frac{p}{q} < 1 \end{aligned}$$

Which tells us that all positive rational numbers $\frac{j}{q}$ can be *uniquely* written as an integer part, i, plus a fractional part $\frac{p}{q}$, where $0 \leq \frac{p}{q} < 1$.

Apply the Euclidean Division Theorem to $\frac{j}{q}$ and let $a_1 = i$. If there is no fractional remainder, then the theorem has been proven.

When there is a non-zero fractional remainder $\frac{p}{q}$, then by the Corollary to Lemma 4 we know that there is a unique factorial-representation for $\frac{p}{q}$.

So $\frac{p}{q} = \frac{a_2}{2!} + \frac{a_3}{3!} + \ldots + \frac{a_n}{n!} \in \mathcal{S}_n$, for some $n \geq 2$, and this sum is uniquely associated with $\frac{p}{q}$. If we choose k such that $a_k \neq 0$ but $a_{k+1} = a_{k+2} = a_{k+3} = \ldots = a_{n-1} = a_n = 0$ then we can satisfy the condition that the last term in the sum is non-zero, and hence:

$\frac{j}{q} = a_1 + \frac{a_2}{2!} + \frac{a_3}{3!} + \ldots + \frac{a_k}{k!}$ is uniquely associated with all positive rational numbers $\frac{j}{q}$.

QED.

Additional Observations

We're guaranteed that $\frac{p}{q} \in \mathcal{S}_q$, but $\mathcal{S}_q$ is not necessarily the smallest such set for which $\frac{p}{q}$ is a member.

For example, the smallest set containing $\frac{p}{5}$, where $0 \le \frac{p}{5} < 1$, is $\mathcal{S}_5$ however the smallest set containing $\frac{p}{6}$, where $0 \le \frac{p}{6} < 1$ is $\mathcal{S}_3$, which is easy to see when we list the contents of a couple of sets,

$$\begin{aligned}\mathcal{S}_4 &= \{\frac{0}{24}, \frac{1}{24}, \frac{2}{24}, \frac{3}{24}, \frac{4}{24}, \frac{5}{24}, \frac{6}{24}, \frac{7}{24}, \frac{8}{24}, \frac{9}{24}, \frac{10}{24}, \frac{11}{24}, \frac{12}{24}, \frac{13}{24}, \frac{14}{24}, \frac{15}{24}, \frac{16}{24}, \frac{17}{24}, \frac{18}{24}, \frac{19}{24}, \frac{20}{24}, \frac{21}{24}, \frac{22}{24}, \frac{23}{24}\} \\ &= \{\frac{0}{24}, \frac{1}{24}, \frac{1}{12}, \frac{1}{8}, \frac{1}{6}, \frac{5}{24}, \frac{1}{4}, \frac{7}{24}, \frac{1}{3}, \frac{3}{8}, \frac{5}{12}, \frac{11}{24}, \frac{1}{2}, \frac{13}{24}, \frac{7}{12}, \frac{5}{8}, \frac{2}{3}, \frac{17}{24}, \frac{3}{4}, \frac{19}{24}, \frac{5}{6}, \frac{7}{8}, \frac{11}{12}, \frac{23}{24}\}\end{aligned}$$

By examination $\mathcal{S}_4$ doesn't contain $\frac{1}{5}$, but it's definitely in $\mathcal{S}_5$ because,

$$\frac{1}{5} = \frac{0}{2} + \frac{1}{2 \cdot 3} + \frac{0}{2 \cdot 3 \cdot 4} + \frac{4}{2 \cdot 3 \cdot 4 \cdot 5} = \frac{1}{6} + \frac{1}{30} = \frac{5+1}{30} = \frac{6}{30} = \frac{1}{5}$$

Also, $\mathcal{S}_3 = \{\frac{0}{6}, \frac{1}{6}, \frac{2}{6}, \frac{3}{6}, \frac{4}{6}, \frac{5}{6}\}$, which demonstrates the claim that $\mathcal{S}_3$ contains $\frac{p}{6}$, where $0 \le \frac{p}{6} < 1$.

I believe that for a given $q \ge 2$ then the smallest set for which the rational number $\frac{p}{q} \in \mathcal{S}_k$, is to pick k such that it is the smallest value for which q divides $k!$.

However, I'll leave that proof for another day.